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SATELLITE GEODESY WITH LASERS

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16. Abstract

Presents a discussion of methods of measuring the Earth's surface using laser methods, satellite tracking methods and mathematical methods. Discusses previous and future accuracies of laser measurements. Gives a discussion on how the accuracy of Earth maps has evolved during the last few years. Discusses the mathematical methods associated with the determination of the Earth's geopotential.

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SATELLITE GEODESY WITH LASERS

D. G. King-Hele

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This article is the conclusion of a major series of articles which have appeared in the magazine "Endeavour" of this year. We have omitted the description of classical geodesy and have only concentrated on the section which deals with the use of the laser (see also LASER No. 2/73, page 20). We have obtained the permission of the ICI, the publisher, as well as the editor of "Endeavour".

Will the 70's be the year of the laser?

When a satellite is observed with a camera, the direction from the camera to the satellite can at best be determined to within one second of arc, which corresponds to an uncertainty of 5 meters at a distance of 1000 km. Using lasers available today, it is already possible to measure the distance between the laser and the satellite with an accuracy of 50 cm: an improvement to 10 cm is probable in the next few years and before 1980 it is possible that an accuracy of 1 cm will be obtained. This will be the case if certain independent limitations can be overcome. Thus, laser measurements already today result in an improvement of a factor of 10 compared with camera measurements, and a further factor of 5 is likely.

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* Numbers in margin indicate pagination in original foreign text.

However, there are two considerable restrictions placed on the use of lasers. A laser used for trajectory tracking sends out a sharp light pulse in the direction of the satellite and the reflected signal is received. The light pulses are extremely sharply focused (tip angle around 0.1°); therefore, the position of a satellite which passes overhead at 8 km/sec must be known very accurately, if one wishes to hit it with a laser beam. In practice, trajectory predictions can already be made for satellites which are sufficiently accurate, because the satellites are only subjected to very small amounts of aerodynamic drag. Therefore, the probability of illuminating satellites with a laser pulse is good, provided the perigee altitude is greater than 600 km. On the other hand, the hit probability for satellites which are subjected to greater braking with perigee altitudes around 200 km is very small; however, it is exactly these trajectories close to the Earth which are necessary for researching the upper atmosphere and for determining the higher harmonics in the Earth's potential. Therefore, cameras will continue to remain important for the analysis of satellite trajectories close to the Earth. The field of diameter is 10° for cameras and the Sun is available as a wide angle light source for them.

Another difficulty connected with tracking satellites with lasers consists of the fact that it is not sufficient to illuminate the satellite with laser light. The satellite must also have a special angular mirror, so that a sufficient amount of light is again thrown back to the measurement point. Up to the present, only seven satellites equipped with such angle reflectors are in orbit around the Earth. Additional satellites of this type are in preparation. Since most of them will remain in orbit for many years, in a few years they will be present in sufficient numbers so that there will be a sufficient selection of longitude and altitude available.

In many countries the production of such laser installations for trajectory tracking of satellites is being energetically pursued. The United States first developed this plan [1]. Therefore, most of the Baker-Nunn stations are equipped with lasers [2]. The same is true for the stations which are under the direct control of NASA [3]. The French also play a leading /25 role, not only in the area of trajectory tracking with lasers but also in the general field of satellite geodesy. They also took the initiative for the International Satellite Geodesy experiment (ISAGEX), which was a very successful observation effort in the years between 1970 and 1971 [4]. Laser trajectory tracking has also been done by stations in Eastern Europe, USSR, West Germany, Japan and Greece. In Great Britain, the Science Research Council is considering a project for a combined laser trajectory tracking device using the Hewitt camera in Malvern.

Even though various types of lasers are used, all of the installations have enough common features so that a short summary of the average trajectory tracking lasers built in 1974 can be made. The usual laser operated by one man (or by two) consists of a ruby rod which transmits about 10 light pulses per minute, each of which is 10 ms long and has an energy of 1 J. The pulses are radiated from a telescope with an opening of 10 cm in the form of a ray bundle with an opening angle of 0.1°. The laser has an automatic controlled deflection installation, so that the satellite trajectory can be pre-selected. (Of course, earlier constructions had a manual control, which was based on visual trajectory observation; today, the trajectory predictions are good enough in general so that automatic firing of the laser is acceptable). The reception telescope has an opening angle of 50 cm and is combined with a photomultiplier, quartz clock and distance counter. Today, an accuracy of 30 cm is possible for distance determinations. A device of the type described costs £60000, or sometimes twice as much. if we are in a country which

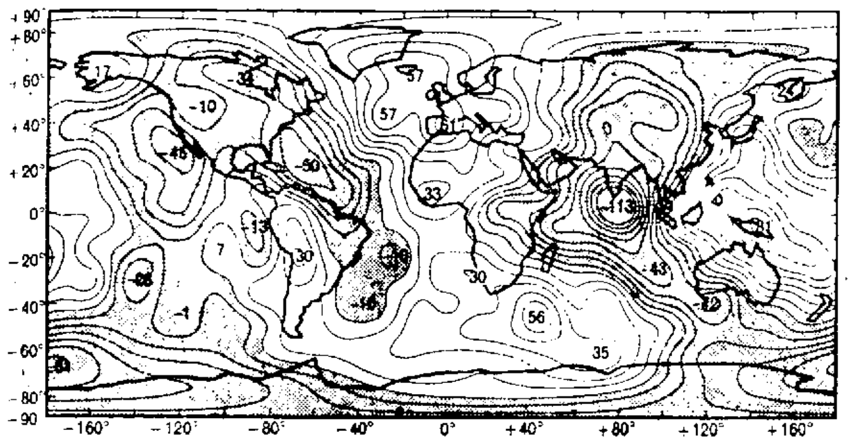

Figure 1. The Smithsonian Standard Earth from the year 1969. The altitude contour lines show the height of the geoid with 10 m intervals referred to a spheroid with the flattening 1/298.255.

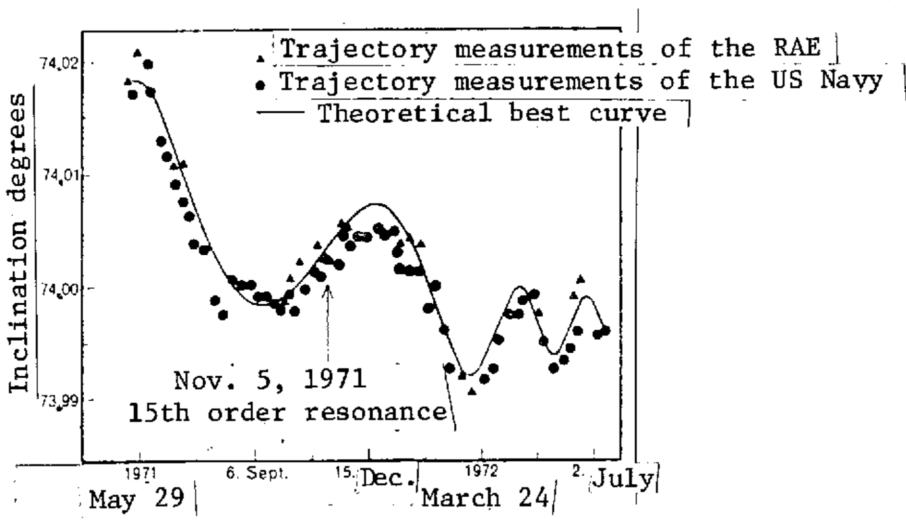

Figure 2. Kosmos 387: Change in the trajectory inclination for a 15th order resonance.

is so concerned with its air passengers that the installation of a radar installation containing a laser is required. The discharge of the laser is blocked if an aircraft enters the beam of the laser.

Already today lasers have made important contributions to measurements on the Earth. The geoid map shown in Figure 1 from 1970 has an overall accuracy of 10 meters, and the local uncertainty is probably only 3 meters. In the meantime, improved geoid maps have been published which use data from laser measurements taken between 1969 and 1972, which are accurate to within 1 m or even 50 cm. They also use extensive gravity measurements on the Earth's surface. Two maps published in 1973, the Smithsonian Standard Earth III [5], as well as the NASA Goddard Earth Model 4 [6], are good examples for this. The outlines of the maps are very similar to Figure 8, but on SSE-III and GEM-4, the sink to the south of India is given as 104 and 112 meters, respectively, and the hill near New Guinea is given as 76 and 73 m, respectively. The hill near England has been displaced towards Iceland and has an altitude of 64 and 67 meters, respectively. The altitude for the hill south of Madagascar is 55 and 50 meters, respectively. The sinks near California and Florida extend to a depth of about 55 meters on both maps. The sink south of New Zealand is 55 meters deep on SSE-III and 63 meters deep on GEM-4. The average altitude error of these maps probably lies around 3 meters, but the accuracy in regions around laser stations is certainly better. The accuracy will improve to the extent that additional laser measurements are considered.

One problem still remains unsolved: to find the exact value of the average radius of the Earth's equator, which is extremely difficult. Various methods result in values for this radius, such as the geometric triangulation using the BC-4 camera, the dynamic method, the range measurement with radio waves as well as Doppler methods [7]. The equatorial radius obtained in this way is around 6,378,140 km, and the scatter is 10 meters, which is still disturbingly large. Even though this inaccuracy does not influence the relative altitude data on geoid maps, we still have a blemish in the otherwise complete picture.

Another contribution of lasers to geodesy is the distance measurements to laser reflectors, which were brought to the Moon by the Apollo astronauts or by the unmanned Russian space vehicles. The technical difficulties are considerably greater than for satellite measurements, because instead of 100 photons, it is necessary to detect a single one. Nevertheless, such measure- / 26
ments have been performed, and their accuracy is similar to that of satellite measurements [8]. These laser measurements on the Moon will probably considerably extend our present day knowledge on the complex motion of the Moon. If the position changes of the Moon reflectors with respect to the Earth center become known, then laser distance measurements to the Moon will contribute important data for geodesy (see LASER No. 4/69, page 19-21).

The Importance of Geodesy in the World of Geophysics

If the inaccuracy of laser geodesy is reduced from 50 cm to 10 cm, and then even down to 1 cm [9], it is then possible to measure the relative motion of laser stations built on various continents over a time period of 5 years or just one year. Using accurate measurements of geoid altitudes, as well as the decay velocity of the lower harmonics in the Earth's potential, it should be possible to derive more accurate data on the probable mass distribution in the interior of the Earth [10]. Already today the wandering of the poles is determined every day and to within 50 cm [11]. Thus factors come into play which would result in the end of speculations. Such measurements could then stimulate research in areas in which the necessary measurement accuracy is missing at the present time.

Of course laser measurements with an accuracy of 10 cm or even 1 cm will not solve all problems in geodesy of the Earth. The accuracy will certainly be restricted to a certain number of measurement locations, and the regions in between will not be measured. In order to produce a truly world-wide map, a theoretical model for the gravitational potential is required. There are various suggestions for assuming the mass distributions in the Earth's interior or at the surface [12, 13]. Independent of this, in general doubly-infinite series of Tesseral harmonics are used, which are truncated arbitrarily (at the 18th order for SSE-III and for the 16th order in the case of GEM-4), so that about 300 coefficients are optimally adjusted to the observation results. However, for this, it is necessary to invert enormous matrices, and their coefficients sometimes have a high degree of correlation, so that the coefficients of higher order which are obtained are quite uncertain. Even if the measurements are more accurate and if the station at work is much more dense, the calculation of so many coefficients will always remain inaccurate. /27

In order to come out of this mathematical labyrinth, a method is required which enables one to directly determine certain coefficients, which are then used as anchor points for the other coefficients. For example, such a method is based on using the resonance effect [14]. It is especially suitable for determining coefficients of the 15th order. A trajectory is called a resonance trajectory, if the trajectory period is exactly such that the trace of the satellite is repeated on the Earth's surface every day. For example, if the Earth turns by exactly 24° with respect to the satellite trajectory during one satellite revolution, then it has turned by exactly 360° after 15 rotations, and the satellite track will repeat itself. Such a trajectory has a 15th order resonance. The Tesseral harmonics of the 15th order have a "bump" in the geopotential every 24° and therefore, have the same effect during each revolution of a resonance trajectory. Therefore, their influence increases every day, and the influence of the other harmonics cancels on the average.

It would be a happy circumstance if a satellite with no aerodynamic drag would have exactly a 13th order resonance. This has been the case only very rarely. On the other hand, a 15th order resonance always occurs when the average altitude of the satellite is about 500 km. Trajectories in this altitude range contract every year because of the influence of aerodynamic drag. Therefore, the aerodynamic drag slowly makes the satellite trajectory pass through the range of the resonance of 15th order. If the transition is slow enough, the resonance effect can be maintained for over a year, so that a considerable change in the trajectory parameter builds up, which can be measured accurately [15]. Figure 2 shows how the trajectory inclination to the equator of Kosmos 387 changed between May 1971 and July 1972 [16]. The fitted theoretical curve gives coefficients of 15th order which are accurate to about 4%. This accuracy is much greater than would be possible within the framework of global solutions. This data is not based on laser measurements, but on observations with the Hewitt cameras and radar, as well as the observations of volunteers using telescopes and stop watches. Laser measurements would not have been possible, because a) the satellite does not have any angle reflectors and b), the strong aerodynamic drag would have made exact trajectory predictions impossible.

In addition to the resonance, there are a few other methods of improving our knowledge of the harmonics of higher order. For example, by measuring the Earth's gravity on the Earth's surface, we can obtain a large amount of detailed information on the harmonics of the 20th and higher orders. In addition, plans exist to install accelerometers which are responsive to gravity force gradients, which can give information about the harmonics of about the same order and which is independent of the previously mentioned methods. It would also be possible to directly measure the shape of the ocean surface by altitude measurements from satellites. If finally one combines a dense network of laser stations for trajectory tracking with the methods mentioned above for finding the gaps, then it is believed that the Earth's surface could be measured to within an accuracy of 5 cm. This is a project which will be realized in the foreseeable future, and the effects of it on geodesy will be enormous.

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